Vol. 147, No. 1 · Research article

DIE ERDE
Journal of the Geographical Society of Berlin

Grèzes litées and their genesis: the site of Enscherange in the Rhenish-Ardennes Massif as a case study

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Manuscript submitted: 19 July 2015 / Accepted for publication: 4 February 2016 / Published online: 22 March 2016

Abstract

The freeze-thaw cycles in periglacial areas during the Quaternary glacials increased frost weathering, leading to a disintegration of rock formations. Transported downslope, clasts allowed in some areas the formation of stratified slope deposits known as "grèzes litées". This study reviews the existing theories and investigates the grèzes litées deposits of Enscherange and Rodershausen in Luxembourg. This process was reinforced by the lithostructural control of the parent material expressed by the dip of schistosity (66°) and its orientation parallel to the main slopes in the area. This gave opportunities to activate the frost-weathering process on top of the ridge where the parent material outcropped. As the stratified slope deposits have a dip of 23° and as there is no significant lateral variation in rock fragment size, slope processes that involve only gravity are excluded and transportation in solifluction lobes with significant slopewash and sorting processes is hypothesized. The Enscherange formation, the biggest known outcrop of grèzes litées in north-western Europe, shows evidence of clear layering over the whole profile depth. A palaeolandscape reconstruction shows that ridges must have been tens of metres higher than presently. The investigation of the matrix composition shows Laacher See tephra in the overlying periglacial cover bed with infiltrations of the minerals in the reworked upper layer of the grèzes litées deposit. Chronostratigraphic approaches using the underlying cryoturbation zone and Laacher See heavy minerals in the overlying topsoil place the formation of grèzes litées deposits in the Late Pleistocene.

Zusammenfassung

Während der quartären Eiszeiten verstärkte der Frost-Tau-Zyklus in den Periglazialgebieten die Frostverwitterung, was zu einem stärkeren Zerfall des anstehenden Gesteins führte. Hangabwärts verlagerter Detritus ermöglichte in einigen Bereichen die Bildung geschichteter Hangablagerungen, die unter der Bezeichnung "*grèzes litées*" bekannt sind. Die vorliegende Studie gibt einen Überblick über die bestehenden Theorien zu diesem Phänomen und untersucht die *grèzes-litées*-Ablagerungen von Enscherange und Rodershausen in Luxemburg. Deren Entstehung wurde verstärkt durch die lagerungsbedingte Streichrichtung im Ausgangsmaterial, die vor allem in der Neigung der Schieferung (66°) und deren Ausrichtung parallel zur vorherrschenden Hangneigung zum Ausdruck kommt. Dadurch wurde der Frostverwitterungsprozess auf dem Kamm, an dem das Ausgangsmaterial ausstreicht, aktiviert. Da die geschichteten Hangablagerungen eine Neigung von 23° aufweisen und es keine signifikanten Unterschiede in der Korngröße des Detritus zu den Seiten hin gibt, können Hangprozesse, die nur auf der Schwerkraft

Nyssen, Jan, Jasper Van Nieuland, Dimitri Vandenberghe, Jérôme Juilleret and *Birgit Terhorst* 2016: *Grèzes litées* and their genesis: the site of Enscherange in the Rhenish-Ardennes Massif as a case study. – DIE ERDE **147** (1): 1-14

DOI: 10.12854/erde-147-1

beruhen, ausgeschlossen werden; stattdessen kann ein Transport in Solifluktionsdecken mit erheblicher Massenbewegung sowie bedeutenden Sortiervorgängen angenommen werden. Die Enscherange-Formation, das größte bekannte Vorkommen von *grèzes litées* in Nordwesteuropa, zeigt Anzeichen einer deutlichen Schichtung über die gesamte Profiltiefe. Eine Rekonstruktion der Paläolandschaft zeigt, dass die Bergrücken mehrere Zehner von Metern höher gewesen sein müssen als heute. Die Untersuchung der Matrixzusammensetzung zeigt Laacher-See-Tephra in der darüberliegenden periglazialen Decke, mit Infiltrationen der Mineralien in die aufgearbeitete obere Schicht der *grèzes-litées*-Ablagerungen. Chronostratigraphische Ansätze, angewandt auf die Kryoturbationszone im Untergrund und die Schwerminerale aus der Laacher-See-Tephra im darüber liegenden Oberboden, verlegen die Bildung der *grèzes-litées*-Ablagerungen ins Spätpleistozän.

Keywords Stratified scree, slope deposits, Pleistocene, Luxembourg, Oesling

1. Introduction

1.1 Relict *grèzes litées* deposits

During the Pleistocene, the Rhenish-Ardennes massif was subjected to severe frost weathering and periglacial processes (*Semmel* and *Terhorst* 2010). This area was never glaciated as it lies outside the limits of the large Pleistocene ice sheets; neither did local glaciers develop as was the case in slightly higher Central European mountain ranges (*Andreoli* et al. 2006, *Metz* 1997, *Raab* and *Völkel* 2003). In the Luxembourgian Ardennes (Oesling), the abandoned quarry at Enscherange shows deposition beds with layered angular rock fragments, supplemented by finer material. Such stratified slope deposits have elsewhere been subjected to detailed descriptive research (e.g. *Guillien* 1964a) defining it as *grèzes litées* deposits, formed of rock fragments with a particle size between 2.5 mm and 25 mm and a fine fraction of 10 % (*lits maigres*) to 20 % (*lits gras*). Previous research on their genesis has led to several hypotheses which all gave specific names to the resulting deposits. One of the most important conditions to initiate the development of *grèzes litées* is the presence of a slope. *Gullentops* (1952) considered *grèzes litées* deposits as the result of a mechanism that includes rock fall, implicating a steep slope gradient leading to the French term of *éboulis ordonnés*. Due to the uncertainty that still exists around the slope steepness, *Bertran* et al. (1992) preferred to use the term *grèzes litées* deposits, as proposed earlier by *Guillien* (1964a,b) and *Journaux* (1976). While this process was ongoing, run-off during warmer periods (i.e. summers or interstadials) drained out the finer fractions, a hypothesis that led to the term slopewash deposits (*Washburn* 1979, *Karte* 1983, *Bertran* et al. 1992).

Both the slopewash and the rock fall hypothesis are still under discussion. Generally accepted characteristics are taken into account to subdivide the *grèzes litées* deposits. It is foolproof that these deposits have a detrital, frost-weathered genesis, classifying them into the category of periglacial cover beds (*Torres-Giron* and *Recio-Especo* 1997, *Semmel* and *Terhorst* 2010, *Terhorst* et al. 2013).

Depending on the resistance to frost weathering of the lithological setting, the amount of detrital material may vary (*Fossen* 2010). Although *grèzes litées* deposits are frequently found in limestone areas (*Guillien* 1964a, *Dewolf* and *Pomerol* 2005), they are also observed in shale-dominated lithological areas (*Karte* 1983, *Riezebos* 1987).

Besides the lithological setting, periglacial conditions have to prevail. As such, the process is ongoing in subpolar regions (Greenland (*Malaurie* 1968), Antarctica (*Bockheim* and *Hall* 2002), Canada (*Hétu* 1995), Svalbard (Norway) (*Jahn* 1960)) and mountain areas such as the Alps (*Bertran* et al. 1992, *Matsuoka* et al. 1997), the Pyrenees (*García-Ruiz* et al. 2001), the Himalaya (*Wasson* 1979) and the Andes (*Francou* 1990). Very often, however, the stratigraphy of the modern deposits cannot be studied because of the absence of incisions in these sediments (*A. Pissart*, personal communication).

Relict sites of *grèzes litées* deposits can be found in areas that were characterized by periglacial conditions in the Upper Pleistocene: in Central Europe (*Karte* 1983, *Semmel* and *Terhorst* 2010), in Mediterranean mountains (*Coltorti* et al. 1983, *Van Steijn* et al. 1984, *Torres-Giron* and *Recio-Especo* 1997), in Great Britain (*Watson* 1965, *Potts* 1971), Ireland (*Hanvey* 1989), Belgium (*Gullentops* 1952, 1954, *Seret* 1963, *Juvigné* 1979, *Pissart* 1976, 1995, *Harris* and *Prick* 2000), Luxembourg (*Riezebos* 1987), France (*Journaux* 1976, *Joly* 1976, *Deshaies* et al. 1995, *Harmand* et al. 1995, *Laurain* et al. 1995, *Ozouf* et al. 1995) or New-Zealand (*Harris* 1975).

1.2 Inferred palaeoenvironmental conditions

The characteristic layering in the *grèzes litées* deposits raised interest from various authors. The main research question was often related to linkages between layering and possible palaeoclimatic changes (*Gullentops* 1952). However, as the layering is generally due to transport processes, including intensive sorting of the rock debris, quantitative palaeoclimatic information has been lost (*Washburn* 1979, *Karte* 1983, *Francou* 1990, *Bertran* et al. 1992, *Van Vliet-Lanoë* and *Valadas* 1992). As the layer thickness is typically in the order of centimetres, it has been linked to the depth of upslope parent rock degradation by frost penetration (*Lautridou* 1985). After downslope transport of the rock debris, new bedrock material outcrops and is subjected to frost weathering. Most authors agree on a seasonal variation within the transport system, but different interpretations remain. One proposed model suggests summer solifluction as the reason for the matrix-supported beds whereas clast-supported beds are the result of a more robust winter transportation (*Tricart* and *Cailleux* 1967, *Coltorti* et al. 1983, *Van Steijn* et al. 1984). This is questioned by *Guillien* (1964b), *Journaux* (1976) and *Karte* (1983) suggesting that summer meltwater washes out the finer fraction, with clast-supported beds as the result, while gelifluction (*Dylik* 1967) and frost creep (*Francou* 1990; *Bertran* et al. 1992) lead to matrix-supported beds. The picture becomes even more complex as also granulometric sorting is observed during transport (*Journaux* 1976, *Washburn* 1979; *Karte* 1983), due to the increased kinetic energy of larger particles and a natural sorting process during transport (*Statham* 1972, *Francou* 1990).

Detailed analysis of the layers resulted, according to *Guillien* (1964a) and *Journaux* (1976), in a "binary system" in which each lobe is divided in two layers, one of coarser and one of finer debris. Several other hypotheses were formulated, such as the "dynamic unit system" of *Francou* (1990) in which a higher friction force of two subsequent clast-supported layers caused easier deposition.

1.3 Earlier investigations in the study area and research objectives

The outcrops in the Oesling (Luxembourg), the study area of this research, are by far larger and better sorted than what has been observed elsewhere in the Rhenish-Ardennes massif (e.g. *Karte* 1983). Though the material was not examined more exactly, *Riezebos* (1987) dated the deposits roughly as Weichselian. No plant remnants or charcoal are found within the layers. In Rodershausen, however, charcoal from the underlying cryoturbation unit was radiocarbon-dated by *Riezebos* (1987) at ~ 50 ka cal BP as maximum age for the formation. This is, more or less, the upper age limit of radiocarbon dating and, thus, the reliability is questioned. However, datings of nearby sites may offer, together with chronostratigraphic techniques, better insights into the age determination (*Semmel* and *Terhorst* 2010). Chronostratigraphic analyses of frost wedges in this cryoturbation unit at Rodershausen (*Riezebos* 1987) led to the establishment of a contemporaneity with the involutions associated with the upper main level of ice wedge casts of the Weichselian deposits of Belgium and the Netherlands, dated as 60-50 ka and 30-20 ka (*Vandenberghe* and *Van Den Broek* 1982, *Vandenberghe* 1983). The datings may be refined by correlation of the *grèzes litées* deposits with the Laacher See eruption (12,900 cal BP), the tephra of which is observed in wide areas of the Rhenish-Ardennes Massif (*Hulshof* et al. 1968, *Juvigné* 1980, *Schmincke* et al. 1999, *Baales* et al. 2002, *Semmel* and *Terhorst* 2010), or with the influx of aeolian loess fractions, although *Paepe* and *Vanhoorne* (1967) indicate a rather limited loess deposition in the Enscherange and Rodershausen area. However, as no hiatuses within the *grèzes litées* deposits are observed, a multiglacial time cover can be excluded. The aim of this study is to investigate the *grèzes litées* deposits of Enscherange (49° 59' 44" N; 5° 58' 38" E) and Rodershausen (50° 2' 31" N; 6° 7' 45" E) – with a magnitude which is exceptional for the Rhenish-Ardennes massif – and their environmental setting and material characterisation, allowing to understand the formation and genesis of *grèzes litées* in a spatio-temporal context of climate and geomorphology.

2. Geological and geomorphological setting

The Luxembourgian Rhenish-Ardennes Massif (Oesling) mainly consists of Devonian schists, phyllites and quartzite. Geomorphologically, it is characterized by a dissected plateau at an altitude of between 400 and 500 m a.s.l., resulting from peneplanations of a series of syn- and anticlinoria, including the Wiltz synclinorium (*Bintz* 2006). During the Pleistocene, periglacial conditions in the area allowed the development of periglacial slope deposits upon which soils developed (*Semmel* and *Terhorst* 2010, *Juilleret* et al.

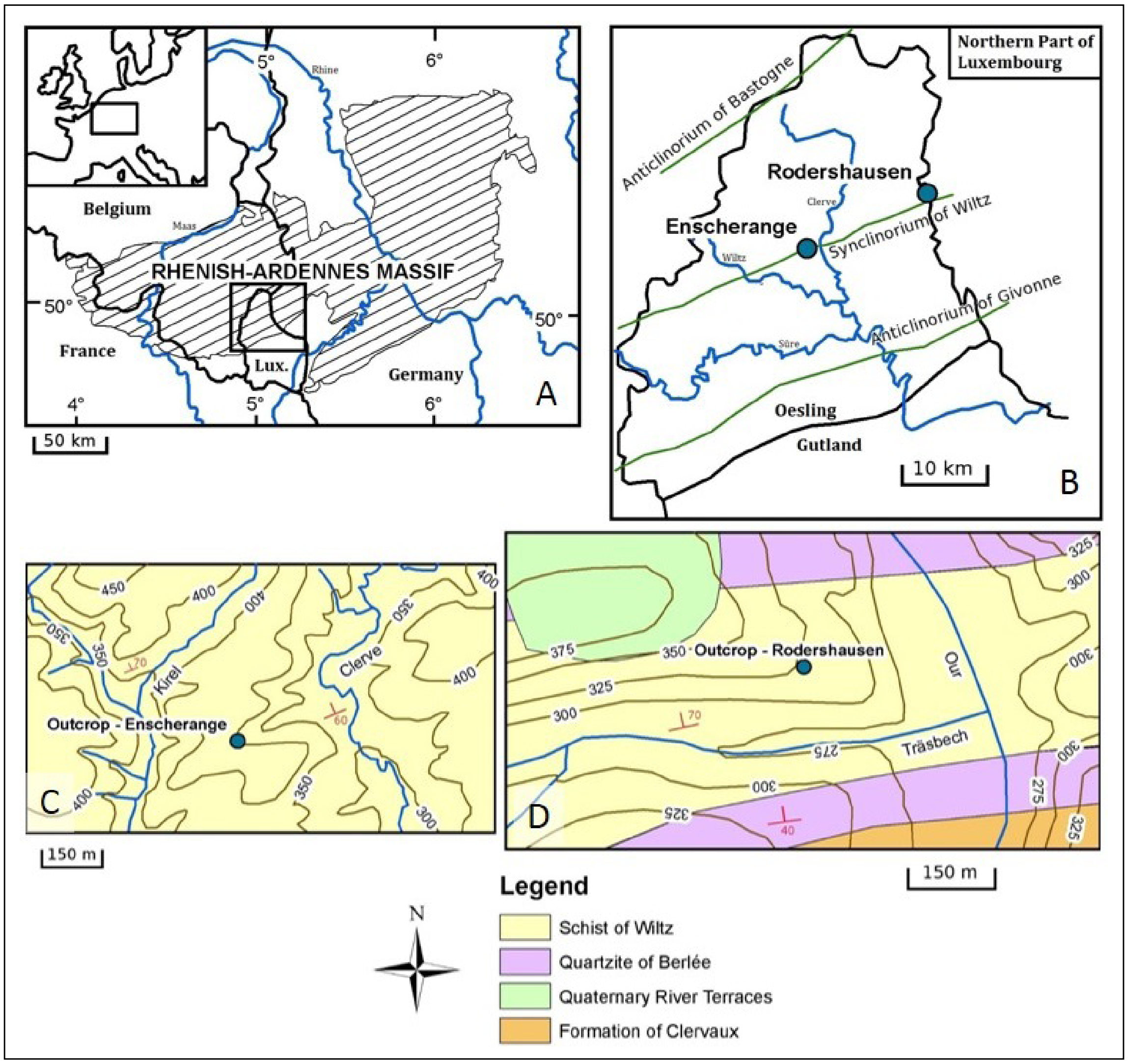

Fig. 1 Location of the two studied grèzes litées outcrops in the Rhenish-Ardennes massif; Enscherange (1C) is located in a less complex lithological setting than Rodershausen (1D); after Lucius (1949).

2011). Near the vicinity of Rodershausen and Enscherange (*Fig. 1*) bedrock has been reworked leading to the development of grèzes litées.

Orientation (65°) and gradient (66°) of the schistosity of the Emsian schist of Wiltz (*Figs. 1C, 1D*), measured near the Enscherange outcrop, are in line with observations by *Lucius* (1949) and *Bintz* (2006) who defined the Wiltz synclinorium as perpendicular to the largest pressure component during the Hercynian orogenesis.

The lithological and topographic setting of Enscherange, in the centre of the Schist of Wiltz formation (*Fig. 1B*), has resulted in a large supply of frost-weathered rock debris leading to a thick deposit of *grèzes litées*. The site is located east of the water divide between the Kirel and Clerve catchments, quite near the top of the ridge. Small valleys differ from the consequent orientation of the main rivers, eroding the ridge in an east-west direction parallel to the schistosity (*Fig. 1C*).

The site (*Fig. 2*) was originally quarried for brick preparation and finally for stable landfill materials. After the abandonment of the quarry in the late 1980s, the vertical walls partly collapsed, leading to the formation of the recent scree slopes on the bottom of the quarry. Four outcropping sections, 2.8 to 5.9 m high, were cleaned, sampled and interpreted.

Compared to the Enscherange quarry, the Rodershausen outcrop is found more downhill, with a more complex lithological setting; as it is located near the village centre (*Fig. 1D*), the outcrop has been more disturbed by anthropogenic interventions. Only one

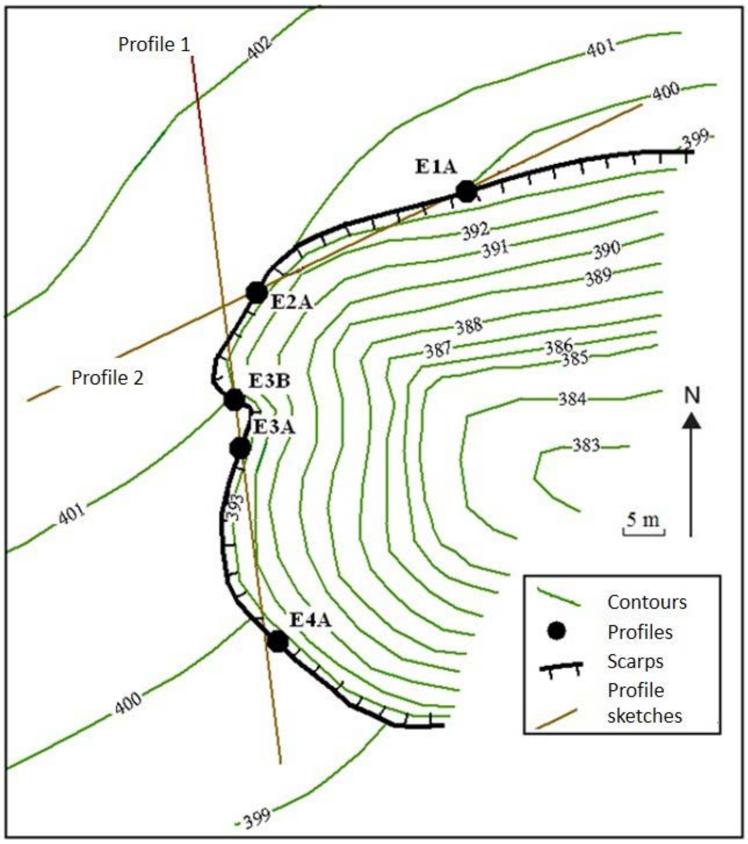

Fig. 2 Map of the Enscherange quarry, showing the overall topography, the steep gradient of the recent screes inside the quarry, and scarps where the grèzes litées and overlaying solifluction deposits are still visible. The locations of the recorded profiles presented in Fig. 4 are indicated.

section (91 cm thick) was interpreted as undisturbed *grèzes litées* deposits and incorporated in this study.

The general geomorphological setting in the area comprises bedrock overlain by different colluvial deposits. A subdivision could be made into four lithostratigraphic units (*Fig. 3*), i.e. from top to bottom: a Holocene topsoil (a), developed upon a solifluction deposit with a stone line at its lower end (b), the *grèzes litées* deposits (c), and the underlying cryoturbated zone (d). In line with earlier observations by *Riezebos* (1987), we could only observe the latter (d) in Rodershausen, as in Enscherange the lower layers are hidden by recent screes (e).

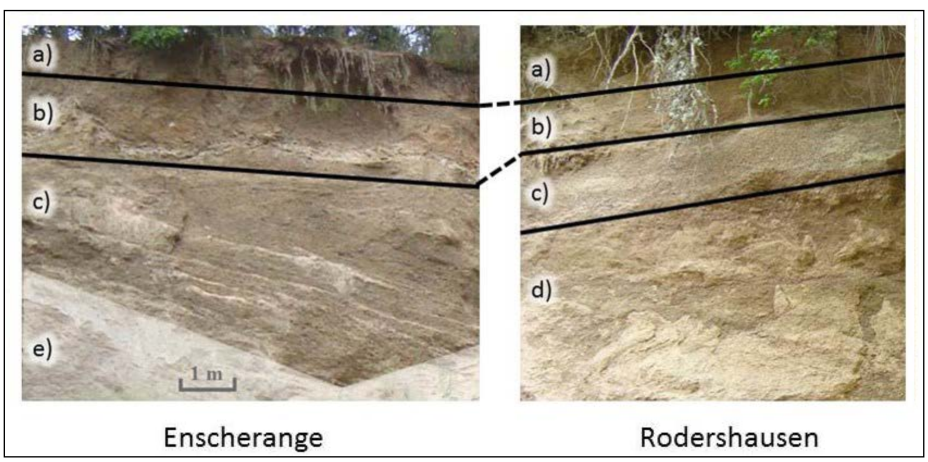

Fig. 3 The general stratigraphical context of the different formations. The grèzes litées formation (c) is overlain by a solifluction layer (b), which is covered by the topsoil (a), in both sequences. Due to the formation of a recent stratified slope deposit (e), underlying cryoturbated structures (d) cannot be observed in Enscherange but only in Rodershausen.

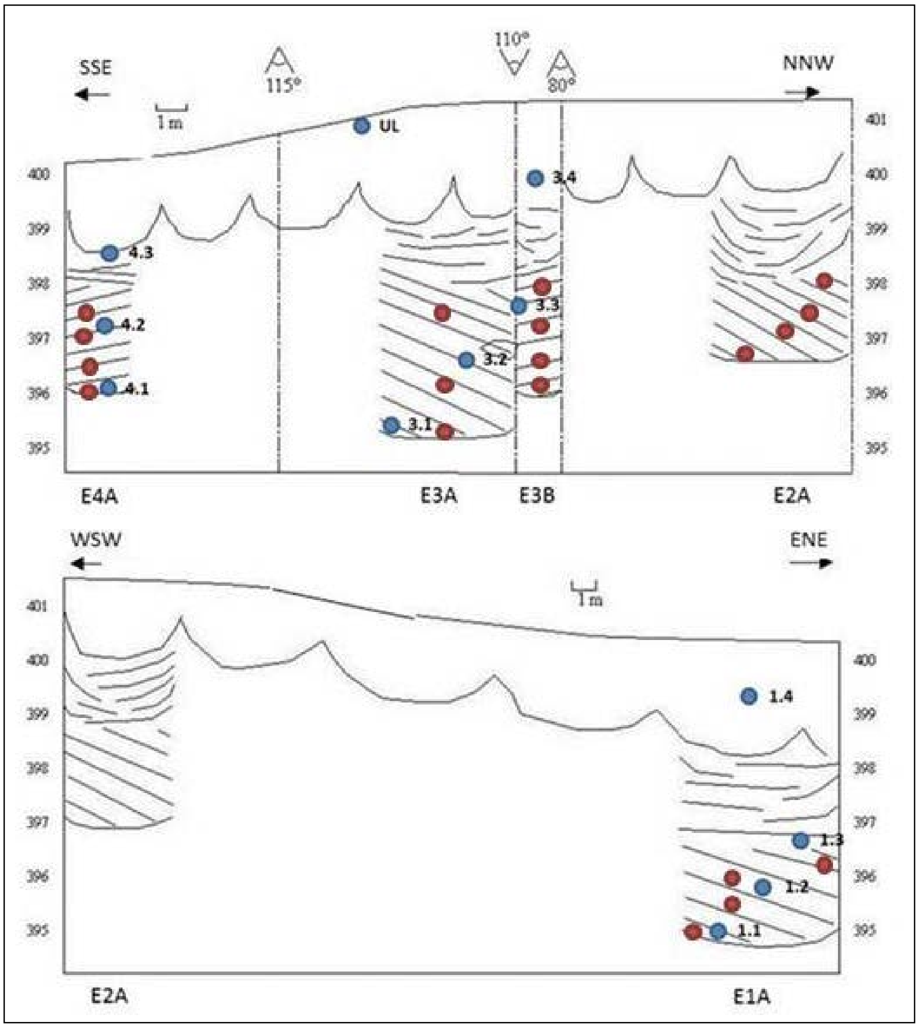

Fig. 4 Synthetic representation of the Enscherange outcrop where we sampled 4 sequences (E1A, E2A, E3A and E3B, E4A) for heavy mineral analysis (n = 12; blue dots) and grain size investigation (n = 19; red dots), in addition to field measurements in 178 layers. The upper profile is indicated as "Profile 1" in Fig. 2, the lower as "Profile 2".

3. Materials and methods

3.1 Analysis of stratification

The analysis of the stratification aims at understanding the depositional conditions of the *grèzes litées* deposits. Jointly with measurements of dip and strike, we reconstructed the palaeotopography of the ridge and considered the possibility of proposed transport hypotheses.

We aimed at interpolating the stratification between profiles at the Enscherange outcrop. Statistical evidence was searched to confirm the applicability of the hypothesis that relates changing layer characteristics to transport distance (*Guillien* 1964a, *Statham* 1972, *Journaux* 1976, *Francou* 1990).

Previous research (*Wasson* 1979, *Coltorti* et al. 1983) divided the layers of the *grèzes litées* deposits into 4 categories taking into account the sorting of the layers and the matrix amount. They can be categorized as openwork bed, a poorly-sorted, high-porous layer; partially openwork bed; clast-support bed; and a matrix-supported bed, a well-sorted, low-porous layer. Due to the difficulties in observation and distinction in the field, *Francou* (1990) reduced the four categories to openwork bed and matrix-rich bed.

Three characteristics were chosen to characterize the individual layers in detail: layer thickness and rock fragment size as macromorphological parameters and matrix composition as a micromorphological parameter. Each transition where one or more characteristics of the *grèzes litées* change indicates a border between two layers. The distance between such borders resulted in the thickness of the layer (precision: 0.5 cm).

3.2 Physical characteristics of the material

The granulometric investigation occurred in two stages. In the field, about 200 cm^3 was sampled from each of the 178 layers; a rock fragment that was visually assumed to represent the D_{50} (i.e. the particle diameter at 50 % in the cumulative distribution) of the layer was selected and its median diameter was measured. Rock fragment sizes were further measured for 19 samples (on average 250 g; indicated with red dots in *Fig. 4*) and granulometric curves were established, from which D_{50} and the interquartile range were obtained. These values were plotted against the estimates of D_{50} obtained in the field for the same layers, allowing an adjustment of all other field estimations.

In line with *Francou* (1990) we classified *grèzes litées* layers into categories according to the relative proportion of fine earth and rock fragments.

To obtain robust data on porosity, 12 undisturbed samples were taken to the laboratory. These samples were weighed at water saturation and weighed again after drying which enabled us to calculate the porosity. As the samples were taken with Kopecki rings having a 5 cm diameter, layers with a thickness < 5 cm could not be sampled for this absolute determination of the porosity.

3.3 Heavy mineral analysis

As the deposits consisted of colluvial frost-weathered rock debris, luminescence dating of this disintegrated bedrock material was not feasible as the small amount of quartz had most probably insufficiently been bleached. However, allochthonous material that is incorporated in the *grèzes litées* added a more robust temporal framework. Hence, the fine sand fraction (63-250 µm) of 12 samples (blue dots in *Fig. 4*) was extracted through sieving and analyzed through a microscope to investigate the influx of allochthonous quartz, screening the feasibility of luminescence dating, and analysed on heavy minerals in order to determine loessic (garnet, epidote and green amphibole) or tephra (titanite, brown amphibole and augite) signatures (*Terhorst* et al. 2013).

4. Results

4.1 Overall stratigraphy

At the major outcrop in Enscherange, when the quarry was still active, *Riezebos* (1987) measured a thickness of 20 m of the *grèzes litées* deposit (*Fig. 3c*). The dip of these deposits (23°) is in line with dips observed in similar deposits in Belgium (*Harris* and *Prick* 2000) and with the expected slope of between 20° and 30° (*Francou* 1990). Post-depositional dis-

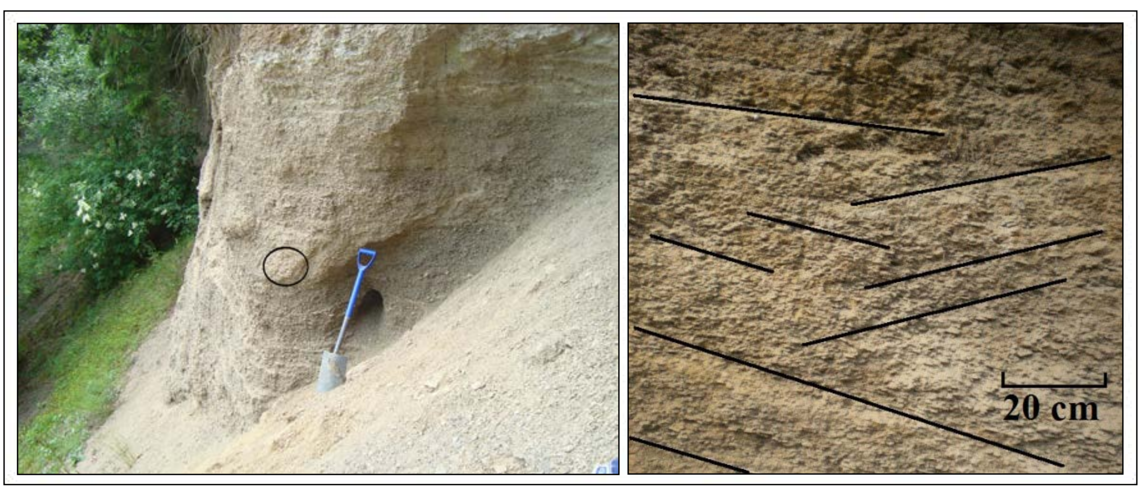

Fig. 5 Post-depositional structures evidence the fluvial reworking of the grèzes litées deposits by meltwater: fluvial lens in profile E3B (left) and cross-bedded structures in profile E2A (right) corresponding to gully fill.

turbances in the *grèzes litées* layering occur as gully incision and infill, fluvial lenses (*Fig. 5a*), cross-beddings (*Fig. 5b*), which evidence the influence of meltwater in periglacial conditions during and after the deposition, as well as frost cracks. An unconformably overlaying solifluction layer of reworked *grèzes litées* is clearly present at both sites (*Fig. 3b*), yielding the most recent part of the formation. This solifluction layer has a clearly different orientation indicating changed topographical conditions. Due to this differential strike of the *grèzes litées* and the overlaying solifluction lobe, outcrop curvature or hakenwerfen (*Sevink* and *Spaargaren* 2005) is found in the upper part of the grèzes litées.

A volumetric estimation, taking into account thickness and strike of the *grèzes litées* (*Van Nieuland* 2011), shows that the former ridge that produced all the frost-shattered debris must have been tens of m higher before the activation of frost weathering.

In Rodershausen, the solifluction layer is limited and the *grèzes litées* deposit is small and poorly preserved, but a large lower unit with cryoturbation is recognizable in which frost wedges were observed by *Riezebos* (1987). Furthermore, on the border between the *grèzes litées* deposits and the underlying cryoturbation unit, a pebble floor indicates an increased action of (melt)water. Rounded quartzite rock fragments, correlated to river terraces, were observed on top of the cryoturbation zone.

4.2 Characteristics of the layers

Though layering is clearly visible, our measurements of thickness, porosity and granulometry did not show any regularity, linear or cyclic trend in the occurrence of layer characteristics. Layer thickness is comprised between 1 and 15 cm. The Enscherange outcrop comprises significantly thicker layers (5.54 ± 0.21 cm) than the Rodershausen outcrop (4.14 ± 0.83 cm), A Welch-test ($p = 0.712$) showed that the thickness does not vary significantly between the four sections in the Enscherange quarry.

In line with *Journaux* (1976), almost all measured rock fragments, except for a few outliers, were smaller than 22 mm, and the fine fraction (< 2 mm) was between 5 % and 20 %. The sorting rate in the layers is rather high, as confirmed by the small inter-quartile ranges (IQR) in the samples (6.1 ± 0.4 mm).

The overall averages of D_{50} of both the field estimations (6.3 ± 0.7 mm) and the laboratory measurements (7.3 ± 0.5 mm) indicate a rather good agreement. A linear regression equation allowed adjusting the field observations of the operator into reliable data for further statistical investigation:

$$Y = 0.6602\ X + 3.1596\ (n = 19;\ R^2 = 0.83;\ P < 0.001) \quad (1)$$

with Y: the adjusted observations and X: the field observations of D_{50} (in mm).

An ANOVA test did not show a significant difference in the grain size distributions among the Enscherange sections; the hypothesis of changing granulometric characteristics when moving away from the bedrock source area (*Guillien* 1964a, *Statham* 1972, *Francou* 1990) could not be proven.

An independent sample T-test showed, similarly to the layer thickness, a significant difference ($P < 0.05$) between the particle size of Rodershausen (6.28 ± 0.24 mm) and that of Enscherange (7.01 ± 0.11 mm).

The porosity of the deposits varies between 20 and 26 % and is independent of the depth in the profile ($R^2 = 0.05$). Only eluviation and illuviation over short distances may have existed, as also stated by *Karte* (1983), *Francou* (1990) and *Bertran* et al. (1992).

4.3 Matrix composition

Under the microscope, the specific composition of the matrix particles (< 250 µm) showed angular-shaped particles, confirming the origin as frost-weathered metamorphic rock. Almost the whole matrix consists of disintegrated schist of Wiltz and non-schist elements are rare.

The amount of heavy mineral particles found was insufficient to allow a statistical analysis. Semi-quantitative data (*Table 1*) show that allochthonous minerals related to loess deposition are not observed in the *grèzes litées* samples. The signature of the Laacher See tephra (LST) (i.e. augite, titanite and brown amphibole) is found in samples 3.4 and 1.4, corresponding to the uppermost *grèzes litées* layers reworked in a solifluction lobe, as well as in the topsoil. The occurring small amounts of micas, especially muscovite and quartz, are typical bedrock components derived from the schist formation of Wiltz.

*Table 1 Abundance of heavy minerals in 12 samples taken in different profiles of the Enscherange outcrop. Sample code and unit enable to find the locations of the samples in combination with Fig. 4. The abundance of the heavy minerals is indicated by * (low; 1-2), ** (medium; 3-5), *** (high; 6-10) and X (abundant; > 10). The different signatures (loess, Laacher See tephra and bedrock material) are represented, as well as alterite, which is a collective term for undefined minerals, and opaque minerals.*

		Loessic components			Laacher See tephra components			Bedrock components				
Sample code	Unit	Garnet	Epidote	Green amphibole	Titanite	Brown amphibole	Augite	Muscovite	Tourmaline	Zircon	Alterite	Opaque minerals
1.1	*Grèzes litées*											X
1.2	*Grèzes litées*	*		*				***				***
1.3	*Grèzes litées*										***	X
1.4	Solifluction lobe, reworked *grèzes litées*				*	*	**	***				X
3.1	*Grèzes litées*							***			***	***
3.2	*Grèzes litées*							***			***	***
3.3	*Grèzes litées*							***			***	***
3.4	Solifluction lobe, reworked *grèzes litées*			*	*	**	*	X		*	X	X
4.1	*Grèzes litées*							X			X	X
4.2	*Grèzes litées*							X	*			X
4.3	Solifluction lobe, reworked *grèzes litées*							X				X
UL	Upper layer/ topsoil	*		**	***	X	***	X		***	***	X

5. Discussion

5.1 On the methodology

Although layer characteristics are often described in the field, some collected data deserve quantitative evaluation. Where layer thickness can be measured in the field, field observations of porosity are inaccurate. What can be estimated in situ is the matrix fraction in the layer. Adjusting field observations to laboratory measurements is incorrect as the material of almost half of the layers is thinner than 5 cm (the diameter of the undisturbed samples for porosity measurements). Moreover, a Spearman correlation test ($r = 0.635$) indicates that the estimation of the amount of matrix in each layer in the field is influenced by grain size. The rather small Pearson correlation coefficient ($r = 0.228$; $P < 0.05$) between layer thickness and granulometry on the other hand indicates an independence of both types of field observations.

5.2 The source area of the frost-shattered clasts

The outcrop in Enscherange is situated in an area almost fully covered by schistose lithology, which has a low resistance to frost weathering (*Fossen* 2010). The main slopes in the area are oriented in the same direction as the dip and strike of the cleavage of the schist of Wiltz. This excellent combination of parameters has led to a strong lithostructural control on the production of clasts from the bedrock and allowed the development of a large *grèzes litées* deposit downslope. Two processes are at stake: (1) the subvertical dip-enhanced water availability that is essential in frost weathering, and (2) the frost-weathered bedrock material could easily be removed in a valley parallel to schistosity, making new outcropping bedrock available for freezing and thawing.

The geological setting in Rodershausen is more complex. Several rock types with different characteristics, such as quartzite and sandstone, outcrop here, and the Our river left some Quaternary river terraces upslope from the *grèzes litées* outcrop. This heterogenic setting leads to a less observable *grèzes litées* deposit. Given the topographical conditions (plan and profile concavities), the Enscherange outcrop acted as a sediment trap, in contrast to the convex situation in Rodershausen. Remarkably, no escarpments of cliffs are present upslope of the *grèzes litées* at Enscherange, but a large planated rock surface; on its way downslope, solifluction material on the plateau that reached the escarpment at the edge would then have developed into *grèzes litées* (*Joly* 1976). Taking into account the deposited volumes of grèzes litées, the pre-*grèzes litées* topography must have consisted of bedrock that reached tens of metres above the current surface of the ridge.

5.3 Processes involved in the formation of the *grèzes litées* deposits

Although earlier measurements of frost penetration into bedrock material varied between 5-10 cm (*Matsuoka* et al. 1997) and 20 cm (*Francou* 1990), our study of *grèzes litées* deposits cannot contribute to this debate, given the intensive sorting during transport. Slopewash and granulometric sorting within solifluction lobes (*Karte* 1983, *Francou* 1990) make that the observed average layer thickness (around 5 cm) is more likely a result of transport sorting rather than of frost penetration in bedrock outcropping upslope. Hence, it is impossible to correlate particular macrosedimentological observations of the *grèzes litées* formation to climatic or seasonal fluctuations.

The fact that all studied layer characteristics do not change significantly through the Enscherange outcrop is a surprising observation. However, as we were only able to evaluate the uppermost metres of a 20 m thick *grèzes litées* packet, this may indicate that the transportation was rather slow, at least, and not long enough to induce intensive sorting leading to important variations in layer thickness as proposed by *Statham* (1972) and *Lautridou* (1985). This hypothesis is strengthened by the location of the outcrop near the top of the ridge.

Given the rather low dip gradient of the Enscherange formation (23°), transportation by rock fall only (*Wasson* 1979) is excluded. Therefore, seasonal transport models based on solifluction, either or not in combination with frost-creep, seem to be more applicable in this setting (*Guillien* 1964b, *Dylik* 1967, *Journaux* 1976, *Karte* 1983, *Francou* 1990, *Bertran* et al. 1992). Although absolute datings through the *grèzes litées* outcrop would be needed to determine how fast this process went on, the large height and the resolution of the Enscherange outcrop indicate that this transport process might have occurred at a fast rate due to the parallel orientation between the schistosity and the slopes. The intense sorting during and after transportation is deemed to induce a layering of matrix and clast-supported beds; indeed, in Enscherange it is almost impossible to recognize seasonal variations in the layer characteristics, in contrast to *Van Steijn* et al. (1984) who thought the clast-supported beds to be a result of transport under snow conditions.

Fig. 6 Different formation processes of grèzes litées are observed in the Enscherange outcrop. The layering reveals no information on palaeoclimatic circumstances but is largely induced by intensive sorting during transport in solifluction lobes: top: binary units (Guillien 1964a) as observed in profile E1A, and bottom: the dynamic unit system (Francou 1990) that occurs rather indistinct in profile E3B.

Depositional factors also deserve a proper discussion. The observed absence of any systematic or cyclic occurrence of layer characteristics may be related to the short transportation distance, whereby internal sorting within lobes could not be fully expressed. Only locally, particularly in Enscherange, the outcropped layered structure gives insights into both transport processes and depositional settings. The binary system of *Guillien* (1964a) can be observed in small parts of the sequences (*Fig. 6a*) as well as the dynamic units system of *Francou* (1990) (*Fig. 6b*). The latter is related to the high topographical position of the *grèzes litées* on the slope. The short transport distance prevented the upper layers from intensive sorting, which induces the higher friction force between the two layers. The Enscherange *grèzes litées* outcrop is located near a ridge formed of outcropping bedrock, indicating that the build-up of the *grèzes litées* deposit reached almost the height of that outcropping bedrock of the ridge, resulting in the submergence (*ennoyage*) of the escarpment by the *grèzes litées* formation and hence exhaustion of supply. At the lower side, larger obstacles (*Francou* 1990) were not observed, but slope and plan concavity and the impossibility for the material to be evacuated further downslope are obvious reasons for deposition.

After deposition, which occurred most probably under periglacial circumstances, warmer periods occurred with an increase of meltwater and rainfall. This led to the presence of small gullies in the upper layers. On top of these, a new system of solifluction lobes of reworked disintegrated bedrock material developed. These lobes are clearly discernible, conforming to descriptions by *Francou* (1990), and have a different direction than the underlying beds of the *grèzes litées*. Later on, erosional processes gave rise to a new valley at the SE of the outcrop towards which the solifluction lobes are directed.

Though not cyclic, a clear organisation in *lits gras* and *lits maigres* is present; hence, despite a porosity of > 20 %, the vertical migration of the finer fraction through the sequence must have been limited; nevertheless, eluviation processes as described in other *grèzes litées* formations (*Karte* 1983, *Francou* 1990, *Bertran* et al. 1992) may not be excluded at a centimetral scale.

5.4 Age of the studied Luxembourgian *grèzes litées* deposits

A microscope analysis of the matrix composition showed a limited to non-existent fraction of quartz or allochthonous wind-blown minerals. Together with the low probability of bleaching of quartz or feldspar minerals during the process, this reduces the feasibility of OSL dating.

The absence of a loess-influenced signature in the *grèzes litées* deposits (*Table 1*) is probably explained by the thin deposits of Pleistocene loess in the study area that are spatially and temporally discontinuous (*Paepe* and *Vanhoorne* 1967). However, a loess admixture was present in the upper layer, and hence loess deposition was possible in principle. The absence of loess in the *grèzes litées* deposits does not allow to classify it as the middle layer of the periglacial cover beds (sensu *Semmel* and *Terhorst* 2010), as, in the sedimentology-based classification of units, the intermediate layer comprises loess and rock fragments. Most probably the *grèzes litées* of Enscherange correspond to the basal layer of the periglacial cover beds.

The occurrence of Laacher See tephra in the periglacial cover beds is generally observed in the Rhenish-Ardennes massif (*Gullentops* 1954, *Semmel* and *Terhorst* 2010) and the presence of the LST in the overlying solifluction lobe, which is infiltrated from the topsoil in which a large signature of LST was observed, is proved by the heavy minerals. As such, the underlying *grèzes litées* deposit in Enscherange was determined older than 12 900 cal BP. Besides that, the layering of the *grèzes litées* deposit was clearly recognizable and a lack of hiatuses (such as soil formation, erosional phases) suggests that the *grèzes litées* deposits were formed during one single period in the Late Glacial or earlier. With the Older Dryas assumed to be too short (several hundred years) to create a 20 m thick set of layers, the Enscherange formation has to be older. Assuming that the Rodershausen site, in which the cryoturbation unit underlying the *grèzes litées* unit is interpreted by *Riezebos* (1987) as approx. 50 ka cal BP (see Section 1.1), may be correlated to the Enscherange outcrop, the maximum age might be 50 ka. It is obvious that in absence of an absolute dating, it cannot be excluded that the studied *grèzes litées* are older than the Late Pleistocene since severe climatic conditions occurred both in the Saalian and Elsterian (*Ehlers* et al. 2011).

6. Conclusions

The periglacial climate conditions during the Late Pleniglacial and the Late Weichselian transformed the pre-existing landscapes. Intense frost weathering eroded the outcropping rock formations of the Wiltz synclinorium and formed colluvial sediments. Under some circumstances *grèzes litées* deposits were formed.

These circumstances are mainly dependent on the lithological characteristics of the parent material. The schist of Wiltz, the most frequent geological formation in the study area, is frost-susceptible, which makes it susceptible for physical erosion, too. This is reinforced by the fast transportation of the cryoclastic material due to the coincidence of schistosity and the main topographic slopes.

The exact transportation model probably differs from other regional settings and is still discussed, but the main processes have been investigated and rock fall models are excluded. Therefore, the term ‘scree’ had to be avoided, in line with *Dewolf* and *Pomerol* (2005). Overland flow may have occurred in summer months, causing slopewash of the uppermost layers. Together with eluviation and illuviation this is assumed to be the major sorting cause.

In addition, the statistical analysis has rejected the lateral variability of granulometry within one *grèzes litées* bed in our study area. The main reason is probably the limited distances in the outcrops in comparison to the distance over which such a phenomenon occurs. This sorting results in a binary system (*Guillien* 1964a) on the one hand and dynamic units on the other hand (*Francou* 1990), both observed in the study area.

Metre-scaled ephemeral incisions of the deposits occurred when seasonal meltwater needed to find its way through topographical lows within the *grèzes litées* deposits.

In order to date the Enscherange and Rodershausen outcrops, several approaches were used. Laacher See tephra was observed in the overlying (reworked) solifluction layer in Enscherange, indicating that the deposition must have occurred before the end of the Late Pleniglacial. The underlying cryoturbation unit in Rodershausen was radiocarbon-dated at 50 ka (*Riezebos* 1987) (but could as well be much older); a contemporaneity with the upper main level of ice wedge casts of the Weichselian deposits (60-50 ka) has also been assumed (*Riezebos* 1987) but it could also date back to Saale or Elster that were extremely cold in this region. Heavy mineral analysis shows no loess signature in Enscherange, which makes it impossible to refine age determination by luminescence dating.

Acknowledgments

This study has benefited from joint field visits with *Frank Flammang* and *Simone Marx* (ASTA, Luxembourg), *Paolo Billi* (Università di Ferrara) and *Amaury Frankl* (Ghent University). *Florias Mees* (Africamuseum) performed mineralogical determinations. Inspiring thoughts came from the late *Albert Pissart* (Université de Liége). *Hanne Hendrickx* carried out a literature review concerning the Pleistocene glaciations in (Central) Europe’s uplands. The authors wish to thank two anonymous reviewers, as well as the editor and working editor for the constructive comments on an earlier version of this manuscript.

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